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ABSTRACT

We present an analysis of the ENEAR sample of peculiar velocities of field and cluster elliptical galaxies, obtained with D_n–σ distances. We use the velocity correlation function, $\psi_1(r)$, to analyze the statistics of the field–object's velocities, while the analysis of the cluster data is based on the estimate of their r.m.s. peculiar velocity, $V_{\rm rms}$. The results are compared with predictions from cosmological models using linear theory. The statistics of the model velocity field is parameterized by the amplitude, $\eta_8 = \sigma_8\Omega_m^{0.6}$, and by the shape parameter, Γ, of the CDM–like power spectrum. This analysis is performed in redshift space, so as to circumvent the need to address corrections due to inhomogeneous Malmquist bias and to the redshift cutoff adopted in the sample selection. From the velocity correlation statistics we obtain $\eta_8 = 0.51^{+0.24}_{-0.09}$ for $\Gamma = 0.25$ at the 2σ level for one interesting fitting parameter. This result agrees with that obtained from a similar analysis of the SFI I-band Tully–Fisher (TF) survey of field Sc galaxies. Even though less constraining, a consistent result is obtained by comparing the measured $V_{\rm rms}$ of clusters to linear theory predictions. For $\Gamma = 0.25$ we find $\eta_8 = 0.63^{+0.22}_{-0.19}$ at 1σ. Again, this result agrees, within the uncertainties, with that obtained from the SCI cluster sample based on TF distances. Overall, our results point toward a statistical concordance of the cosmic flows traced by spirals and early-type galaxies, with galaxy distances estimated using TF and D_n–σ distance indicators, respectively.

Subject headings: Cosmology: observations – cosmology: theory – galaxies: distances and redshifts – large-scale structure of universe.

1 INTRODUCTION

The analysis of the peculiar velocities of galaxies and clusters is one of the most promising ways to investigate the amplitude of cosmic density perturbations on $\sim 100h^{-1}$ Mpc 1Mpc scales (e.g., Strauss & Willick 1995). The importance of cosmic flows for cosmology has motivated a two-decade long effort of building large and homogeneous redshift-distance samples of galaxies and clusters. Analyses of early redshift-distance surveys of spirals (Aaronson et al. 1982) and of early-types (e.g. Lynden-Bell et al. 1988), even though leading to the development of several statistical methods of analyzing peculiar velocity data, left many issues unresolved, primarily because they were based on relatively small and shallow data sets. Recently, a second-generation of redshift-distance surveys has become available involving high-quality data and significantly larger samples of both spirals (Mathewson, Ford & Buchhorn 1992; Haynes et al. 1999a,b) and early-types (da Costa et al. 2000a). The existence of these new samples has raised the hope that some of the discrepancies found in earlier analyses may soon be settled. Indeed, the analyses of the different all-sky catalogs of peculiar velocity data currently available such as Mark III (Willick et al. 1997) and SFI (e.g. da Costa et al. 1996; Giovanelli et al. 1998), lead to a roughly consistent picture of the peculiar velocity field and the local mass distribution (Dekel et al. 1999). However, some quantitative disagreements still remain ranging from the amplitude of the bulk velocity (da Costa et al. 1996; Giovanelli et al. 1998; Dekel et al. 1999), to estimates of the parameter $\beta = \Omega_m^{0.6}/b$ (e.g., Davis, Nusser & Willick 1996; Zaroubi et al. 1997; da Costa et al. 1998; Willick & Strauss 1998; Freudling et al. 1999; Borgani et al. 2000), where Ω_m is the cosmological matter density parameter and b is the linear galaxy biasing factor. It is important to emphasize that the two most important catalogs currently in use, Mark III and SFI, consist of combinations of distinct data sets covering different parts of the sky and therefore could be susceptible to subtle systematic effects. Both catalogs also rely predominantly on Tully-Fisher distances of spiral galaxies and we should note that earlier statistical comparisons of the velocity fields derived from $D_n - \sigma$ and TF distances found significant differences between them (e.g., Górski et al. 1989; Tormen et al. 1993). There have also been claims of significant differences, larger than expected from the estimated errors, between cluster distances estimated using galaxies of different morphological types (e.g. Mould et al. 1991; Scodeggio, Giovanelli & Haynes 1998).

In this context, the recently completed all-sky redshift–distance survey of early-type galaxies (da Costa et al. 2000a, hereafter ENEAR), probing a volume comparable to that of the existing catalogs of peculiar velocity data, is a welcome addition. The ENEAR galaxies sample different regions of space and density regimes; the peculiar velocities are measured using an independent distance indicator; and the distances are based on separate types of observations, reduction techniques and corrections. Finally, the ENEAR sample has well defined selection criteria, the completeness of the observations is uniform across the sky and the data, mostly new measurements by the same group, are in a homogeneous system.

The present Letter has the twofold aim of comparing global statistical quantities, which describe the velocity fields traced by the TF and $D_n - \sigma$ distance indicators, and of placing constraints on the nature of the fluctuation power–spectrum. Our analysis is based on the velocity correlation statistics and the r.m.s. one-dimensional peculiar velocity of clusters. These statistics were used by Borgani et al. (2000, B00 hereafter) and Borgani et al. (1997, B97 hereafter) to analyze the SFI sample of field spirals and the SCI sample of cluster spirals (Giovanelli et al. 1997), respectively. In this paper, the same analysis is carried out for the ENEAR sample of field galaxies and groups and for ENEAR clusters (hereafter ENEARc; Bernardi et al. 2000, in preparation).

2 THE DATA

The ENEAR sample contains 1359 ellipticals brighter than $m_B = 14.5$ with $D_n - \sigma$ measured distances and 569 cluster galaxies in 28 clusters (ENEARc). Galaxies have been objectively assigned to groups and clusters using the information available from complete redshift surveys sampling the same volume. Our analysis is performed in redshift–space so as to avoid correcting for inhomogeneous Malmquist bias and the redshift cutoff adopted in the sample selection. Therefore, we use the inverse $D_n - \sigma$ template derived by Bernardi et al. (2000, in preparation) combining all the cluster data. Below, we limit our analysis to objects within $cz = 6000\,\mathrm{km\,s^{-1}}$, so as to exclude those with very uncertain velocity measurements. This sub-sample consists of 355 field galaxies and 223 groups. In the cluster sample analysis we only consider the 20 clusters with $cz \leq 6000\,\mathrm{km\,s^{-1}}$. Of these, we discard the clusters CEN 30 and CEN 45; these systems lie along the same line-of-sight and are close in redshift-space making the assignment of galaxies to individual systems difficult. They are also suspected to form a bound system (Lucey & Carter 1988) and their large peculiar velocities observed may be due to non–linear effects. We also pay special attention to two other groups, AS714 and AS753, both with large peculiar velocities ($\sim 900\ \mathrm{km\,s^{-1}}$). These systems lie in the region of the Great Attractor and may also be subject to non–linear dynamical interactions. Below we discuss the impact of including or excluding these two systems in the analysis.

3 THE VELOCITY CORRELATION STATISTICS

Our analysis of the velocity correlation statistics follows closely that presented in B00. We refer to that paper for a more thorough discussion. We use the velocity correlation estimator originally introduced by Górski et al. (1989, G89 hereafter):

$$\psi_1(r) \;=\; \frac{\sum_{|\mathbf{r}_i-\mathbf{r}_j|=r} u_i u_j \cos\vartheta_{ij}}{\sum_{|\mathbf{r}_1-\mathbf{r}_j|=r} \cos^2\vartheta_{ij}}\,, \qquad (1)$$

where ϑ_{ij} is the angle between the direction of the i-th and the j-th object and the sums are over all the pairs at separation r in redshift space. In eq.(1) u_i is the radial peculiar velocity of the i–th object and we assign equal weight to all objects, so as to minimize the effect of cosmic variance (see the discussion in B00). The average of $\psi_1(r)$ over an ensemble of cosmic flow realizations is $\Psi_1(r) = \langle\psi_1(r)\rangle \;=\; \mathcal{A}(r)\Psi_\parallel(r) + [1-\mathcal{A}(r)]\,\Psi_\perp(r)$, where $\Psi_\parallel$ and $\Psi_\perp$ are the radial and transverse correlation functions of the three–dimensional peculiar velocity field (see G89). In linear theory, they are connected to the power–spectrum of density fluctuations, $P(k)$, according to

$$\begin{aligned}
\Psi_\parallel(r) \;&=\; \frac{f(\Omega_m)^2\,H_0^2}{2\pi^2}\int dk\,P(k)\left[j_0(kr) - 2\frac{j_1(kr)}{kr}\right]\;; \\
\Psi_\perp(r) \;&=\; \frac{f(\Omega_m)^2\,H_0^2}{2\pi^2}\int dk\,P(k)\,\frac{j_1(kr)}{kr}\,, \qquad (2)
\end{aligned}$$

where $j_i(x)$ is the i-th order spherical Bessel function and $f(\Omega_m) \simeq \Omega_m^{0.6}$. The quantity $\mathcal{A}(r)$ is a moment of the selection function of the sample, which is fully specified by the spatial distribution of the objects in the sample (e.g., Górski et al. 1989; B00). Therefore, the model ψ_1 can be computed taking into account the specific sampling through the $\mathcal{A}(r)$ function. The velocity correlation function $\psi_1(r)$ for the ENEAR sample is plotted in Figure 1 up to $r = 3500\,\mathrm{km\,s^{-1}}$, for all objects within $cz = 6000\,\mathrm{km\,s^{-1}}$. This separation range has been shown by B00 to be that where ψ_1 is more stable for the SFI sample, which has about the same size as ENEAR. We choose the bin size to be $500\,\mathrm{km\,s^{-1}}$ in order to keep these errors relatively small within each separation bin. We verified that final constraints on the model parameter are left unchanged by halving the bin width. For the purpose of comparing ENEAR and SFI results, we show in Figure 1 only the statistical errors due to the internal noise of the data set, which have been estimated as follows. At the position of each galaxy we add to the observed peculiar velocity a random component which is drawn from a Gaussian distribution having r.m.s. dispersion equal to the observational error reported for that object. Velocity correlations are then computed for 1000 realizations of this perturbed data set and errors on ψ_1 are estimated at each separation from the scatter among these realizations. Cosmic variance must not be included here, since ENEAR and SFI probe cosmic flows within the same region of the Universe.

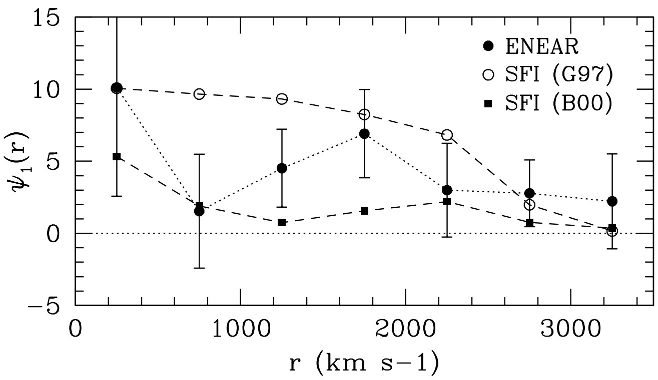

Fig. 1.— The velocity correlation function, $\psi_1(r)$ (in units of $10^4\,\mathrm{km\,s^{-1}}$), for the ENEAR sample (filled circles). Open circles and squares are the results for the SFI sample, as derived by B00 from two different zero–point calibrations of the TF relation. Errorbars, that for reasons of clarity are only reported for ENEAR, are the 1σ uncertainties from the internal sample noise (see text).

Remarkably the ψ_1 velocity correlation of the ENEAR sample falls just between the two SFI estimates, based on the two zero–point calibrations of the TF relation presented by B00. This result contrasts with the disagreement originally found by G89 between spirals (Aaronson et al. 1982) and ellipticals (Lynden-Bell et al. 1988). We use the ENEAR velocity correlation function to place constraints on cosmological models by following the same procedure discussed in B00, and only briefly summarized here. We run N–body simulations for different cosmological models, and extract from each of them a fairly large number (256) of independent mock ENEAR samples. In each mock sample, "galaxies" are placed in the same positions as in the real sample. The peculiar velocity of each mock galaxy is then perturbed with a Gaussian–distributed component associated to the observational error of its real counterpart. With this procedure, each set of mock samples includes both cosmic variance and statistical noise. Therefore, we estimate the elements of the covariance matrix $\mathcal{C}^{ij} = N_{mock}^{-1}\sum_{l=1}^{N_{mock}}\left(\psi_{1,l}^i - \bar{\psi}_1^i\right)\left(\psi_{1,l}^j - \bar{\psi}_1^j\right)$, where $\psi_{1,l}^i$ is the value of the velocity correlation function at the i–th separation bin for the l–th mock sample, and $\bar{\psi}_1^i$ is its ensemble average. Based on this approach, B00 showed that (a) linear theory provides a good description of the velocity correlation statistics of the N–body simulated samples; (b) the relative amount of covariance, i.e. the values of $C^{ij}/\psi_1^i\psi_1^j$, is independent of the underlying cosmology.

Based on these results, we compute a grid of linear–theory model predictions for $\psi_1(r)$, as well as the elements of the corresponding covariance matrix expected for a sample the size of ENEAR. We assume the power spectrum expression $P(k) = A\,k\,T^2(k)$, where the transfer function, $T(k)$, is assumed to have the CDM–like form with the k–dependence specified by the shape parameter Γ. The amplitude of $P(k)$ is expressed in terms of σ_8, the r.m.s. fluctuation amplitude within a sphere of $8\,h^{-1}$Mpc. Therefore, following eq.(2), $\psi_1(r)$ is entirely specified by the two parameters Γ and $\eta_8 = \sigma_8\Omega_m^{0.6}$. In order to derive constraints on these parameters, we compute the weighted χ^2 between the ENEAR correlation function, ψ_1^{ENEAR}, and that from model predictions, ψ_1^{mod}, taking into account the covariance terms. The probability for model rejection is estimated, from the value of $\Delta\chi^2 = \chi^2 - \chi^2_{min}$, assuming a χ^2 statistic, where χ^2_{min} is the absolute minimum value.

In Figure 2 we plot the iso–$\Delta\chi^2$ contours corresponding to 1σ and 2σ confidence levels. The degeneracy of the constraint in the η_8–Γ plane is due to the fact that the coherence of the flow on a given scale depends not only on the overall amplitude of the power-spectrum but also on its slope. This is because peculiar velocities are generated non–locally, so that coherence of the flow on a given scale can be associated either to fluctuations on comparable (large η_8 and Γ) or on much larger scales (small η_8 and Γ). Fixing $\Gamma = 0.25$, consistent with galaxy clustering data (e.g., Dodelson & Gaztanaga 1999), we find $\eta_8 = 0.51^{+0.24}_{-0.09}$ at the 2σ level for one interesting fitting parameter. We verified from the analysis of the mock samples that redshift–space distortions have a negligible effect in the estimate of $\psi_1(r)$, with the resulting constraints on η_8 being affected at most by about 5%. As expected from the comparison shown in Fig. 1, this result is in good agreement with that derived by B00 from the analysis of the SFI TF-survey of spiral galaxies. Therefore, we confirm that, for reasonable values of the power spectrum shape, the velocity correlation statistics favor small power–spectrum amplitudes. Although at variance with other analysis of velocity fields based on maximum likelihood analysis of the velocity correlation statistics (e.g. Zaroubi et al. 1998; Freudling et al. 1999; see the discussion in B00), this result agrees with independent constraints on the amplitude of the power spectrum, like those imposed by the number density of local galaxy clusters (e.g., Eke et al. 1996; Girardi et al. 1998).

4 The r.m.s. VELOCITY OF CLUSTERS

The r.m.s. peculiar velocity of clusters has been used by several authors as further means to set constraints on cosmological parameters (e.g., Moscardini et al. 1996; Bahcall & Oh 1996; B97; Watkins 1997). This analysis is repeated here for the ENEAR cluster sample. The observational estimate from the ENEAR sample ranges from $V_{\rm rms}^{\rm obs} = 450 \pm 73\,\mathrm{km\,s^{-1}}$ to $V_{\rm rms}^{\rm obs} = 470 \pm 68\,\mathrm{km\,s^{-1}}$ for the samples of 16 and 18 clusters, respectively, defined in Section 2 by either excluding or including AS714 and AS753. The error is the 1σ scatter over 10^5 random realizations of the real sample, each generated from a Gaussian distribution having the above $V_{\rm rms}$ and velocities convolved with the observational errors. From the theoretical side, linear theory for the growth of density fluctuations predicts that the one–dimensional r.m.s. velocity is

$$V_{\rm rms} = \frac{H_0 f(\Omega_0)}{\sqrt{3}} \left[\frac{1}{2\pi^2}\int_0^\infty dk\, P(k)\, W^2(kR)\right]^{1/2}, \quad (3)$$

where we use the expression $W(kR) = \exp(-k^2R^2/2)$ for the window function. Croft & Efstathiou (1994) verified that eq.(3) provides a rather good fit to results from N–body simulations for R values in the range 1.5–3 h^{-1}Mpc. In the present analysis we adopt $R = 1.5\, h^{-1}$Mpc, but point out that the results are largely insensitive to the exact choice. For instance, assuming R twice as large only increases the final constraints on η_8 by about 8%.

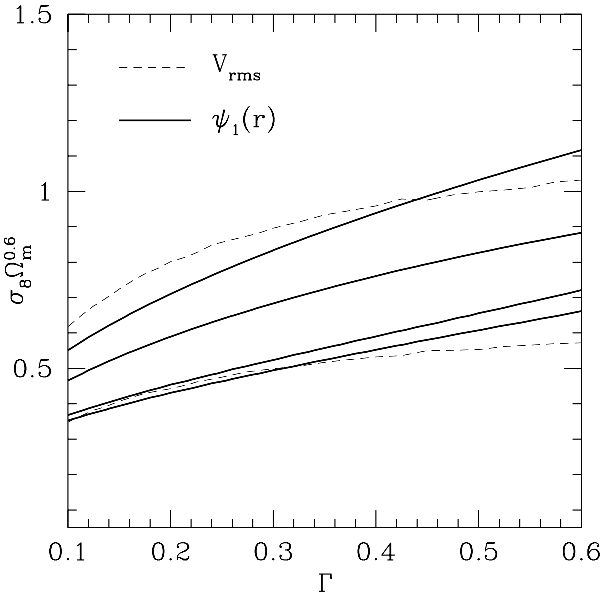

Fig. 2.— The 1σ and 2σ contours in the η_8–Γ plane from the analysis of the velocity correlation function, $\psi_1(r)$, for ENEAR groups and galaxies. Also shown with the dashed contours is the 1σ confidence limits from the analysis of the r.m.s. peculiar velocity of ENEAR clusters.

The procedure to establish the confidence level for a given model is the same as applied by B97. Let v_i and σ_i be the velocity and its error for the i-th real cluster ($i = 1, \ldots, 16$). For a given model, we generate Monte-Carlo samples, each containing 16 velocities, V_i, drawn from a Gaussian distribution, with dispersion provided by eq.(3). For each sample, every cluster's velocity is estimated as a Gaussian deviate of the mean V_i and dispersion σ_i, and the r.m.s. velocity of the sample is then computed. For each model we generate $N = 10^4$ samples and then compute the fraction $\mathcal{F}$ with $V^j_{\rm rms}$ ($j = 1, \ldots, N$) at least as discrepant as $V^{obs}_{\rm rms}$ with respect to their average value, $N^{-1}\sum_j V^j_{\rm rms}$. Therefore, the smaller the value of $\mathcal{F}$, the larger the probability for model rejection. After determining the highest value of $\mathcal{F}$, relative confidence levels are computed by determining standard decrements with respect to this maximum value (i.e., $\Delta\mathcal{F} \simeq 0.68$ and 0.95 for 1σ and 2σ exclusion levels). The resulting 1σ constraints on the Γ–η_8 parameter space are shown in Fig. 2 (dashed curves). Although this result is less constraining than that obtained from the velocity correlation analysis, it nicely overlaps with it, thus demonstrating that ENEAR clusters and field galaxies consistently trace the same large–scale flows. For $\Gamma = 0.25$ we find $\eta_8 = 0.63^{+0.22}_{-0.19}$ at the 1σ confidence level. This result is also consistent with that previously obtained from similar analyses of the SCI cluster velocities (B97, Watkins 1997). The inclusion of the AS714 and AS753 clusters in our analysis would only increase the resulting η_8 by about 5%.

5 CONCLUSIONS

We presented statistical analyses of the peculiar velocity field within $cz = 6000\,{\rm km\,s^{-1}}$ traced by field objects and clusters in the ENEAR sample based on D_n–σ distances. We use the velocity correlation statistics $\psi_1(r)$ to characterize the velocity field traced by field ellipticals and loose groups ad find results which are consistent with those obtained from the SFI sample of spirals with TF distances. Contrary to past claims, we find no statistically significant differences between the peculiar velocity fields mapped by spirals and ellipticals. This result is in general agreement with and generalizes the findings of da Costa et al. (2000b) using the bulk-velocity statistics. Constraints on the power spectrum of density fluctuations were derived by resorting to linear theory. Assuming the shape of the power spectrum to be consistent with results from galaxy galaxy clustering analyses, $\Gamma = 0.25$, we find $\eta_8 = 0.51^{+0.24}_{-0.09}$ at 2σ level for one interesting fitting parameter. A consistent constraint is also obtained from the analysis of the r.m.s. velocity of ENEAR clusters; for the same value of the shape parameter Γ, it implies $\eta_8 = 0.63^{+0.22}_{-0.19}$ at 1σ, thus consistent with results from the SCI cluster TF velocities (B97, Watkins 1997). Our results confirm the conclusion by B00 that the amplitude of cosmic flows can be reconciled with independent constraints on the amplitude of density perturbations as that required by the number density of nearby rich clusters. They also show that consistent results are obtainable from independent distance indicators, once they are applied to homogeneously selected galaxy samples.

SB wishes to thank ESO for the hospitality during the preparation of this work. The authors would also like to thank C. Rité and O. Chaves for their contribution over the years. The results of this paper are based on observations at Complejo Astronomico El Leoncito (CASLEO), Cerro Tololo Interamerican Observatory (CTIO), European Southern Observatory (ESO), Fred Lawrence Whipple Observatory (FLWO), Observatório do Pico dos Dias, and the MDM Observatory at Kitt Peak.

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